PRACTICAL ISSUES IN REAL-WORLD IMPLEMENTATION OF STRUCTURAL HEALTH MONITORING SYSTEMS

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ABSTRACT

Currently, there exist several different types of structural health monitoring (SHM) systems that are in the stage of development and/or are being tested for use in real-world applications. For a number of years, Structural Health Monitoring (SHM) systems have demonstrated feasibility in laboratory and controlled testing environments. Acellent has been developing and testing strategies to bring the SHM field to the next level. These include issues involved with system installation, calibration, reliability and connections for structures fabricated with composite materials. Composite structures are susceptible to hidden or barely visible damage caused by impacts and/or excessive loads that if unchecked may lead to lower structural reliability, higher life-cycle costs, and loss in operational capability. Current maintenance and inspection techniques for in-service composite structures can be labor-intensive and time-consuming. Utilization of an integrated sensor network system such as that developed by Acellent can greatly reduce the inspection burden through fast in-situ data collection and processing. Using a built-in network of actuators and sensors, Acellent Technologies is providing the tools required for a practical SHM system. In this paper, key development and testing issues concerning real-world implementation of the SHM system on composite structures are presented.

Keywords: Structural Health Monitoring; SMART Layer®; SMART Suitcase™; Built-in/embedded sensors, Piezoelectric, Sensor network, reliability, calibration

1. INTRODUCTION

The performance and behavior characteristics of nearly all in-service structures can be affected by degradation resulting from sustained use as well as from exposure to severe environmental conditions or damage resulting from external conditions such as impact, loading abrasion, operator abuse, or neglect. These factors can have serious consequences on the in-service structures as related to safety, cost, and operational capability. Therefore, the timely and accurate detection, characterization and monitoring of structural cracking, corrosion, delamination, material degradation and other types of damage are a major concern in the operational environment.

In recent years, Structural Health Monitoring is increasingly being evaluated by the industry as a possible method to improve the safety and reliability of structures and thereby reduce their operational cost. Structural health monitoring technology is perceived as a revolutionary method of determining the integrity of structures involving the use of multidisciplinary fields including sensors, materials, signal processing, system integration and signal interpretation. The core of the technology is the development of self-sufficient systems for the continuous monitoring, inspection and damage detection of structures with minimal labor involvement. The aim of the technology is not simply to detect structural failure, but also provide an early indication of physical damage. The early warning provided by an SHM system can then be used to define remedial strategies before the structural damage leads to failure.

A built-in structural health monitoring system would consist of three major components:

- sensors/sensor network,
- integrated hardware, and
- software to monitor in-situ the “health” condition of in-service structures

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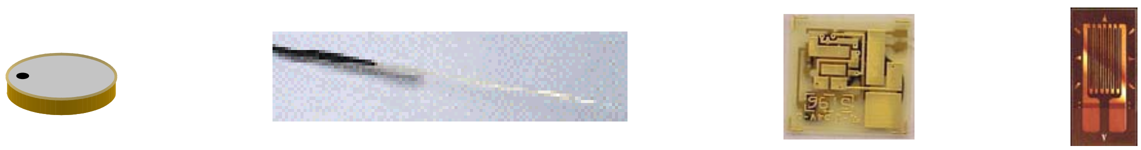
An important part of the system is the proper integration of the sensors and actuators with the structure. Although sensors can be integrated individually with a structure, a novel and cost-effective method would be to integrate a network of sensors with the structure. This sensor network when combined with more sophisticated data acquisition systems and diagnostic software can drastically reduce the cost of inspection, allow for more frequent maintenance schedules and reduce the likelihood of catastrophic structural failures.

Currently there exist several types of sensors that can be used for structural health monitoring. These include piezoelectric, fiber-optic, MEMS, strain-gages etc. The maturity and networking capability of the various sensor types depends on the conditions of usage and structural application.



Piezoelectric Fiber-optic MEMS Strain-gages

Figure 1: Example of the types of sensors used for structural health monitoring

2. PRACTICAL ISSUES

There are several issues involved in the practical usage and implementation of structural health monitoring systems using the sensors defined above. These include:

- Sensor integration
- Calibration
- Reliability
- Effect of Environmental Conditions

These practical issues are discussed by using an example of piezoelectric materials. Piezoelectric sensors and actuators are made of piezoelectric materials (piezo-crystals, ceramics, and polymers). Materials that have a piezoelectric effect convert mechanical force to electrical charge, and vice versa. Hence, piezoelectric materials can be used as both sensors and actuators. As sensors, they produce an electrical signal when they are physically deformed (strained). As actuators, they physically deform (expand, contract, or shear) when an electrical charge is applied. Using this property, piezoelectric materials can be used to measure stress and strain and can also be used to mechanically excite the structure to propagate stress waves and induce internal vibrations. Inputting a time-varying electrical signal to any of the actuators/sensors causes a propagating stress wave or propagating mechanical deformation to emanate from the sensor/actuator and travel through the material for detection by a plurality of neighboring sensors/actuators.

The piezoelectric materials can be used in two sensing modes – active and passive. In Active Sensing Mode, the actuators are externally excited to generate pre-selected diagnostic signals and transmit them to neighboring sensors whose response can then be interpreted in terms of damage location and size or material property changes within the structure. In Passive Sensing Mode the piezoelectric sensors can be used as continuously monitored sensors that “listen” for external impact events.

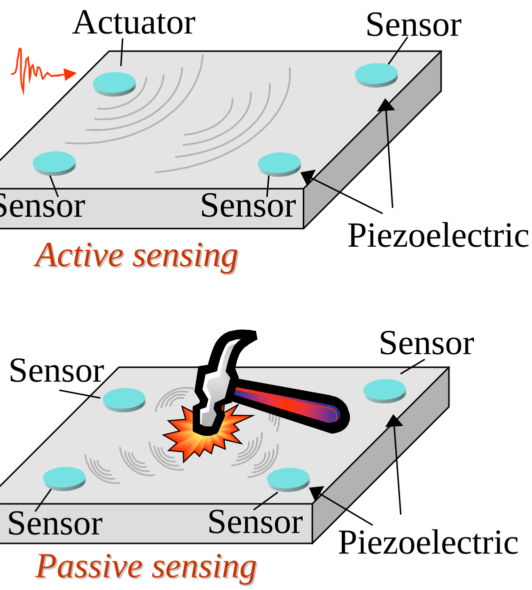


Figure 2: Active and Passive Sensing modes used by piezoelectric materials

Sensor/ Sensor Network Integration: Sensor network based piezoelectric structural health monitoring systems are commercially available from Acellent. Piezoelectric sensor networks embedded on a thin film called the SMART Layer®, can be used for easy integration of a large number of sensors.

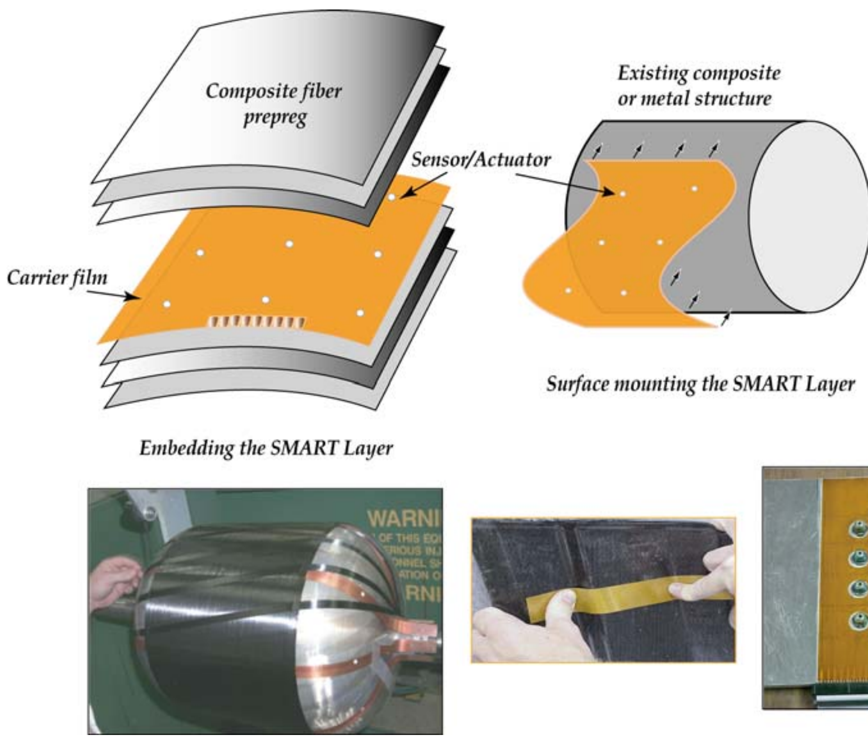


Figure 3: Piezoelectric sensor based SMART Layer® network integration

The SMART Layer® is well established in the field of Structural Health monitoring and is currently known for its unique ability to provide a wider structural coverage for gathering data with its network of sensors/actuators embedded on a layer thus eliminating the need for each sensor to be installed individually. The layer consists of a network of embedded, distributed piezoelectric discs (PZT – lead-zirconate-titnate) acting as both sensors and actuators for monitoring structural condition in real time. The SMART Layer® manufacturing process utilizes the printed circuit technique in order to connect a large number of sensors embedded in the layer. The layer can be as thin as 4 mil, has almost negligible weight and provides excellent electrical insulation. Typical PZT sizes used include 0.25” diameter and 10-30 mil thickness.

The SMART Layer® is treated as an extra ply that can be placed between composite plies during composite layup process. After co-curing in an autoclave, the resulting composite structure would have an integrated network of piezoceramics that can be used to send and receive diagnostic signals for monitoring the structure. The process of embedding a SMART Layer® inside composite materials does not alter the composite manufacturing process. The SMART Layer® can also be surface mounted on a variety of structures including both metallic structures and composite structure. For metallic structures, the SMART Layers® are bonded onto metal surfaces using a secondary adhesive such as epoxy. Figure 3 shows the schematic of the SMART Layer® integration process and its integration into filament wound composites and metal structures.

Calibration: As mentioned above, the PZT can be used in dual sensing modes, passive and active. In the passive sensing mode, the structural health monitoring system

- Finds location of impacts
- Records date/time of occurrence.
- Determines impact force/energy (to predict structural damage)

No calibration is required for impact location. However, in order to determine the impact force/energy, calibration with known impact forces is required. This can be typically done with the use of an instrumented hammer as shown in Figure 4.

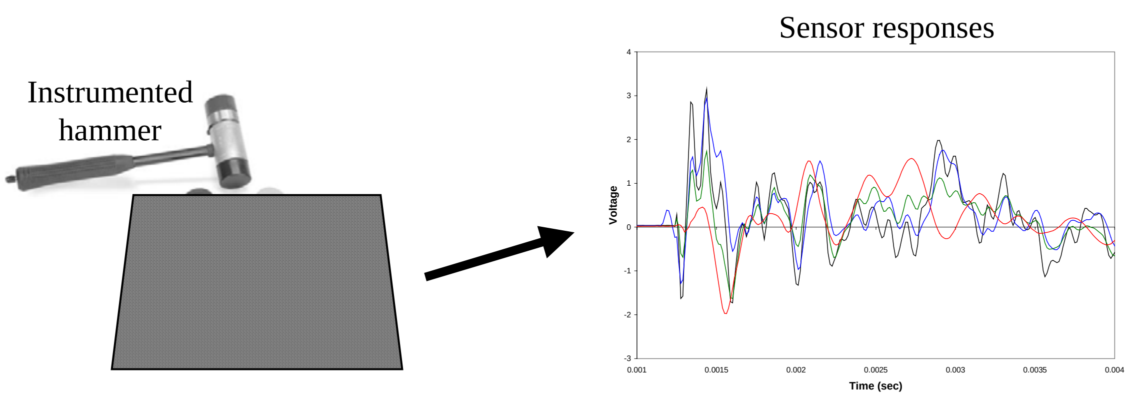


Figure 4: Calibration of impact force with instrumented hammer

In the active sensing mode, the structural health monitoring system

- Finds location of structural changes
- Can scan large areas in minutes.
- Can identify type/size of damage

In order to locate structural changes and detect structural damage, there is no calibration required. Calibration with a known damage size is required in the case of damage size quantification.

Reliability: The piezoelectric SMART Layer® based structural health monitoring system was subjected to a variety of usage scenarios in order to tests for sensors and system reliability. These include, misuse tests that subjected metal and composite parts instrumented with piezoelectric sensor networks to

- Environmental conditions (heat, rain, snow)
- Projectile impacts
- Intense fatigue testing to > 13 million cycles
- Changes in boundary conditions (location of supports, added mass)

The results proved that the piezoelectric sensors and the structural health monitoring system are able to withstand a variety of structural usage conditions.

Effect of Environmental Conditions: Environmental conditions such as temperature can in some cases, affect the signals obtained from the sensors. Figure 5 shows an example of changes in signals due to variation in temperature.

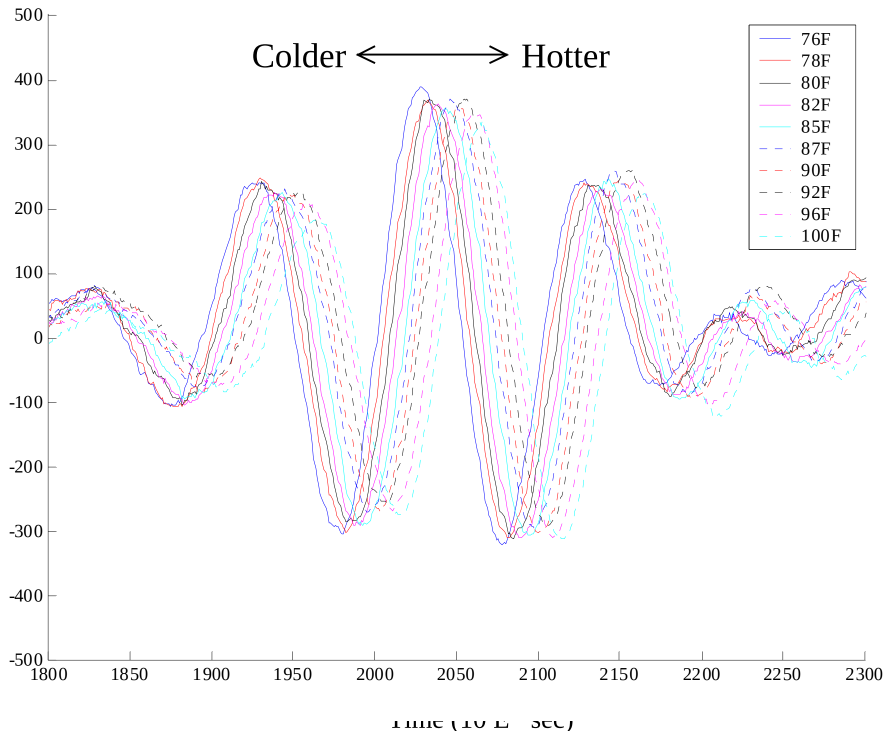


Figure 5: Example of variation in signals with temperature

The changes in temperature can however, be calibrated based on the structure and application. Figure 6 shows one example of a filament wound structure with embedded SMART Layers®. In this application, SMART Layer® were designed and manufactured to be embedded in a filament wound composite bottle. The bottle has 8 evenly spaced strips with 5 piezoelectric sensors each, for a total of 40 sensors. Four of these strips were placed during filament winding one-ply above the aluminum liner while the remaining four were placed one-hoop ply below the surface of the bottle. The bottle was subsequently cured resulting in a structure with embedded piezoelectric sensors. This bottle however, is sensitive to variations in temperature. If these variations are not removed, then the resulting signals make it difficult to distinguish between damage and temperature changes.

Figure 6 shows the composite bottle heated locally using a heat gun. Simultaneously, damage was simulated using a sticky patch manufactured with a tape like substance. The sticky patch simulates damage by locally absorbing so of the energy from the transmitted signals. When subjected to active sensing, it can be seen that the change in structure due to temperature and due to damage are both seen clearly. However, after temperature compensation, the temperature effect can be removed, leaving only changes due to damage visible.

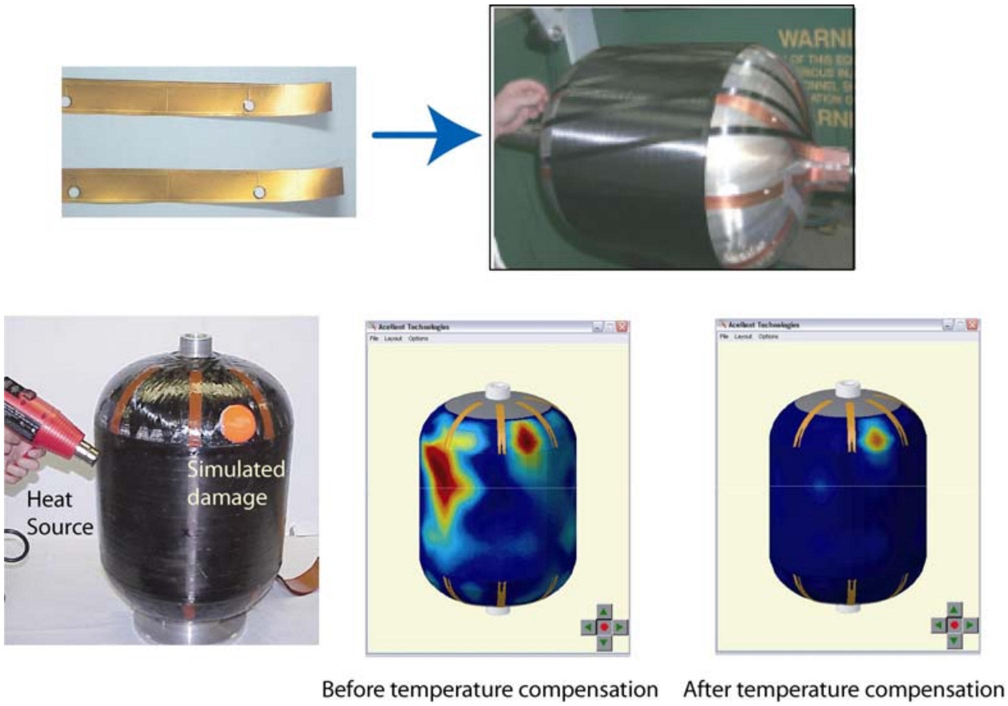


Figure 6: Effect of temperature and temperature compensation for filament wound bottle

3. SUMMARY

This paper provides an overview of the practical issues that need to be considered for the implementation and usage of structural health monitoring systems. The issues are discussed in detail with the help of an example, piezoelectric based structural health monitoring system. Issues and solutions for integration of sensors and sensors networks have been presented along with some examples. Two types of piezoelectric based systems are discussed – active and passive sensing systems. Calibration requirements for each type of system and reliability issues are also discussed. Finally, the effect of environmental conditions such as temperature are also discussed. This is done with the help of an example of filament wound composite structure with embedded piezoelectric sensors. Results of active interrogation of the structure with and without temperature compensation are also presented. .

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